Pearson BTEC Levels 4 Higher Nationals in Engineering (RQF)

Unit 13: Fundamentals of Thermodynamics and Heat Engines

Unit Workbook 1

in a series of 4 for this unit

Learning Outcome 1

Fundamental Thermodynamic Systems

1.1 Fundamental Systems:

1.1.1 First Law of Thermodynamics

Purpose

Thermodynamics is the study of behaviour and dynamics of energy. The first law of thermodynamics is simple: “energy cannot be created or destroyed, it can only be transferred from one form to another”.

1.1.2 Forms of energy and basic definitions.

Theory

Energy comes in a wide variety of forms, for example; if your lightbulb was powered by a gas power station, the energy changes several times before coming out of the bulb as light and heat, shown by Fig.1.1. None of the processes will be 100% efficient, and realistically will lose a lot of temperature as heat.

Fig.1.1: An energy flow chart from gas to a lightbulb.

Fig.1.1 shows several different energies, but energy can be categorised into larger groups:

- Kinetic energy is the energy of a moving object, in Fig.1.1, this would be the generator’s shaft spinning to generate electrical energy
- Potential energy is the energy that an object has due to its position relative to others, for example, electrical energy moves from high charge to low charge. Or an object on a table has more potential energy than an object on the floor.
- Internal energy is the energy that is holding the bonds of the molecules together, such as the chemical energy holding a fuel’s molecules together.

1.1.3 Definitions of Systems and Surroundings

Theory

A system is defined as either open or closed, and where the system meets its surroundings is called the boundary. A closed system is one that only has an input or output of energy in some form, shown by Fig.1.2, the boundary encloses the entire system, a closed system is typically used when modelling an engine’s cylinder.

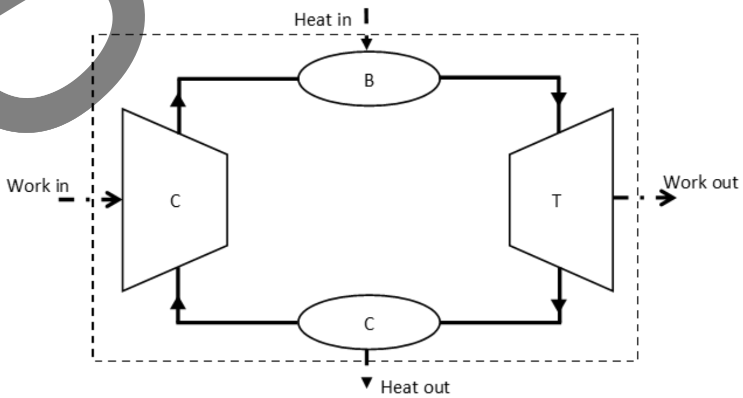

Fig.1.2: A diagram of a closed system, the labels on the system will be explained Section.1.1.6

An open system also has a mass flow, the boundary will surround the equipment, but will also have an intake and exhaust of mass through the boundary. Most thermodynamic systems will use an open system, such as heat pumps and refrigeration cycles.

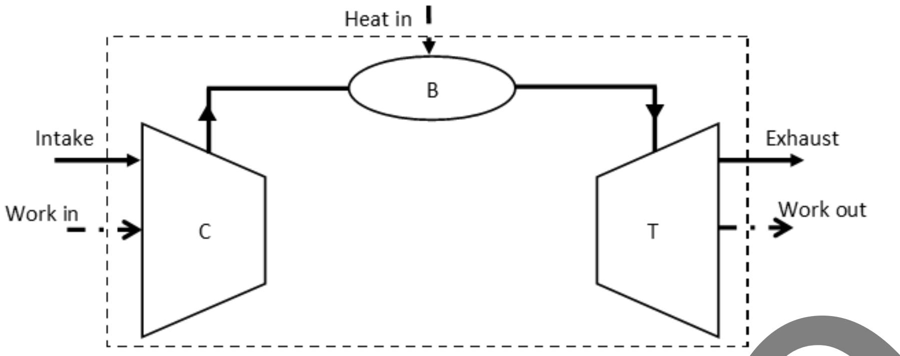

Fig1.3: An open system and its boundaries

1.2 Fundamental Equations

1.2.1 Applying the First Law to Systems

Theory

The first law of the system can be calculated as Eq.1.1 simply the summation of energies, where U is the internal energy of the molecules, PE is the potential energy, and KE is the kinetic energy.

$$E = U + \sum PE + \sum KE \qquad \text{(Eq.1.1)}$$

Meaning a change in energy is modelled as Eq.1.2.

$$\Delta E = E_2 - E_1 = U_2 - U_1 + \mathrm{KE}_2 - \mathrm{KE}_1 + \mathrm{PE}_2 - \mathrm{PE}_1 \qquad \text{(Eq.1.2)}$$

Since the system is closed, it can be assumed that there is no flow in the system, meaning that $KE = PE = 0$. And so, the change of energies between two points can be shown as Eq.1.3, where Q is the heat transferred, and W is the work transferred.

$$U_1 + Q = U_2 + W \qquad \text{(Eq.1.3)}$$

Which turns into the standard thermodynamic equation that is Eq.1.4.

$$Q - W = U_2 - U_1 \qquad \text{(Eq.1.4)}$$

For an open system however, the equation is Eq.1.5.

$$Q - W = U_2 - U_1 + \mathrm{KE}_2 - \mathrm{KE}_1 + \mathrm{PE}_2 - \mathrm{PE}_1 \qquad \text{(Eq.1.5)}$$

1.2.2 Moles

Theory

Before moving onto gas laws, a brief explanation of the term "moles" is required. Moles define the number of atoms or molecules that are present in a material. The equation to calculate the number of moles, n, is given by Eq.1.6, where m is the overall mass of the substance, and M_r is the molecular mass of the substance.

$$n = \frac{m}{M_r} \qquad \text{(Eq.1.6)}$$

For example, one mole of Helium (atomic mass 4) would weigh 4 grams. To find the number of atoms or molecules present in the substance, the number of moles is multiplied by Avogadro's constant ($N_A = 6.022 \times 10^{23} mol^{-1}$).

Example 1

Find the number of molecules present in:

a) $3.5g$ of methane
b) $80g$ of Sodium Chloride

Answers:

a) Methane's chemical formula is CH_4, meaning there are 4 Hydrogens ($M_r = 1$) to every Carbon ($M_r = 12$), so the total molecular mass is $(4 \times 1) + 12 = 16$.

   The number of moles is therefore $n = \frac{3.5}{16} = 0.2188 mol$

   Which then gives the number of atoms as $0.2188 \times 6.022 \times 10^{23} = 1.32 \times 10^{23}\ atoms$

b) Sodium Chloride's chemical formula is $NaCl$. One chlorine atom($M_r = 35.5$) for every sodium atom ($M_r = 23$),the total molecular mass is $35.5 + 23 = 58.5$

   The number of moles is therefore $n = \frac{80}{58.5} = 1.3675$

   Which gives the number of atoms as $1.3675 \times 6.022 \times 10^{23} = 8.24 \times 10^{23} atoms$

1.2.3 The Ideal Gas Equation

Theory

When the working fluid is modelled as a gas, it is useful to model it as an "ideal gas". An ideal gas is an imaginary substance that obeys the relationship in Eq.1.7, where P is the pressure, V is the volume, n is the number of moles, R_u is the universal gas constant ($8.314 J \cdot mol^{-1} \cdot K^{-1}$) and T is the temperature in Kelvin.

$$PV = nR_uT \qquad \text{(Eq.1.7)}$$

We can also change the ideal gas equation to incorporate the mass of the gas in question, by using the individual gas constant R, which is calculated using Eq.1.8.

$$R = M_R R_u \qquad \text{(Eq.1.8)}$$

In which case the ideal gas equation develops into Eq.1.9.

$$PV = mRT \qquad \text{(Eq.1.9)}$$

One of the most common mistakes is not converting the temperature to Kelvin when applying the ideal gas equation. Kelvin is simply the temperature in $°C + 273$ ($20°C = 293K$).

1.2.4 Ideal Gas Laws

Theory

Some ideal gas laws can be used to see changes in an ideal gas system under a certain condition. The main ones are Charles' Law, Boyle's Law and the general gas law.

Boyle's Law: "For a fixed mass of gas at constant temperature, the volume is inversely proportional to the pressure" which can be expressed mathematically as Eq.1.10

$$PV = \text{constant} \qquad \text{(Eq.1.10)}$$

Which, given that n is fixed, R_u is a constant, and T is constant by the law's demands, is consistent with the ideal gas equation.

Charles' Law: "For a fixed mass of gas at constant pressure, the volume is directly proportional to the temperature" which is expressed as Eq.1.11

$$V = \text{constant} \times T \qquad \text{(Eq.1.11)}$$

Since n is fixed, R_u is a constant and P is constant by the law's demands, Charles' law is consistent with the ideal gas equation.

General Gas Law: By combining the two laws together we produce the gas law, shown by Eq.1.12.

$$\frac{PV}{T} = \text{constant} \qquad \text{(Eq.1.12)}$$

So, if one of the variables change, the other two variables will change accordingly, which can be expressed as Eq.1.13.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad \text{(Eq.1.13)}$$

1.2.5 Perfect Gas Equations

While we have just discussed an ideal gas, but we have to also talk about the concept of a "perfect gas". A perfect gas is one that has constant specific heats across all temperatures. The specific heats are more important when working with systems with large temperature differences in Unit 38: Further Thermodynamics; but for this unit, we will only consider working with perfect gases. We can calculate the individual gas constants by using the specific heat at constant pressure c_p and the specific heat and constant volume c_v using Eq.1.14

$$c_p - c_v = R \qquad \text{(Eq.1.14)}$$

The ratio of the specific heats, γ, is also important in calculations which will be discussed in Section.1.2.6. But the equation for finding γ is Eq.1.15.

$$\frac{c_p}{c_v} = \gamma \qquad \text{(Eq.1.15)}$$

1.2.6 Pressure-Volume Diagrams

Theory

When analysing the thermodynamics of a system, one of the first steps is to develop its pressure-volume (P-V) diagram. With volume on the x-axis and pressure on the y-axis. Fig.1.4 shows the P-V diagram of a standard air heat engine. The area enclosed by the graph is the work done by the system.

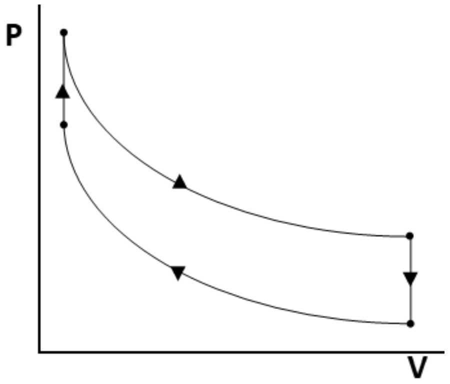

Fig.1.4: P-V diagram of a heat engine, discussed in more detail in workbook 4

P-V diagrams can also help show the work output of the system. The work is the useful energy used to create movement, such as a drive shaft of a generator or a car. The area enclosed in the graph is the work done by the system. Work can be calculated using Eq.1.16.

$$W = \int P\, dV \qquad \text{(Eq.1.16)}$$

Knowing the overall net work done by the system will give the efficiency of the system in Eq.1.17.

$$\eta = \frac{W_{net}}{Q_{IN}} \qquad \text{(Eq.1.17)}$$